

Characterization of Voltage and Charge Transfer in AC Gas Discharge Displays

Abstract: New techniques have been applied to the characterization of voltage and charge transfer in ac gas discharge display cells. This paper presents a new method of measuring the voltage transfer curve and several aspects of the operation of the cells which are revealed by these measurements. In the steady sustain region the voltage transfer is nearly equal to the initial gas voltage. Over most of the voltage transfer curve, the voltage transferred is independent of the history and operating environment of the test cell. On the other hand, the charge transfer does depend upon these factors. The voltage and charge transferred vary differently with the initial gas voltage, so the effective wall capacitance depends upon the initial wall voltage as well as on history and environment. This is attributed to the dependence of the lateral spread of the discharge upon its strength.

Introduction

New techniques have been applied to the measurement of the electrical characteristics of single cells of ac gas discharge displays, especially voltage and charge transfer. A major motivation of this work is to provide experimental data upon which to base the adjustment of the detailed physical processes modeled and the values of empirical parameters in computer simulations. This combination of simulation and experimental characterization has proved to be a powerful tool for obtaining a clearer physical understanding of the operation of these displays. In addition, it provides engineering data on the effects of design and material changes in gas panels and a basis for devising new electronic drive techniques. The present paper concerns itself with the measurement of voltage and charge transfer and with some aspects of the operation of ac plasma cells as revealed by these measurements. The numerical simulation model and the relationship between physical processes and cell operation are the subjects of publications by C. Lanza and O. Sahni [1-3].

Voltage and charge transfer

A simplified cross section through one cell of a gas display panel is shown in Fig. 1. Layers of glassy insulating material separate the electrodes from the gas space. The contribution to the capacitance between opposing electrodes due to these insulating layers is characterized as capacitor C_w' while the contribution of the gas space is characterized as a "gas" capacitance C_g' . Following Johnson et al. [4], we represent the gas discharge as a

dependent current generator i_g' in parallel with C_g' . If the externally applied voltage is added as generator V_a , the equivalent circuit of Fig. 2(a) is obtained. The authors have, for convenience, adopted a different sign convention for the dependent generator and so have also adopted alternative symbols for equivalent circuit components. The voltage across the gas gap V_g' is determined by superposition of the contributions of the applied voltage and the i_g' generator:

$$V_g' = KV_a + V_w', \quad (1)$$

where

$$V_w' = - \int i_g' dt / (C_w' + C_g'),$$

and

$$K = C_w' / (C_w' + C_g').$$

In the equivalent circuit of Fig. 2(a), the external current due to i_g' alone is equal to Ki_g' and is called i_g . From Eq. (1) and the quantities $V_g = V_g'/K$ and $V_w = V_w'/K$,

$$V_g = V_a + V_w. \quad (2)$$

Voltages V_g and V_w may be thought of as the internal voltages referred to the external terminals. If we choose to neglect displacement currents due to changes in V_a , the simple equivalent circuit of Fig. 2(b) is obtained. By convention [4], the voltage and current divisions of the de-

Copyright 1978 by International Business Machines Corporation. Copying is permitted without payment of royalty provided that (1) each reproduction is done without alteration and (2) the *Journal* reference and IBM copyright notice are included on the first page. The title and abstract may be used without further permission in computer-based and other information-service systems. Permission to *republish* other excerpts should be obtained from the Editor.

tailed equivalent circuit are ignored and the quantities V_w and V_g , which can be inferred from measurements on the external terminals, are referred to as the wall voltage and gas voltage, respectively. The wall capacitance C_w of Fig. 2(b) is equal to KC'_w and models the storage site for voltage and charge:

$$C_w = - \int i_g dt / \Delta V_w = - \Delta Q / \Delta V_w,$$

where the integral is taken over a single discharge period. The quantities ΔQ and ΔV_w are the charge transfer and the voltage transfer due to the discharge. The value of the factor K is typically 0.95, so the approximations leading from Fig. 2(a) to 2(b) are quite reasonable for purposes of characterization of charge and voltage transfer. However, when one is concerned with the effects of changes in panel materials or dimensions, it is necessary to account for changes in K due to changes in the relative values of C'_g and C'_w .

The foregoing derivation assumes the linearity of the equivalent circuit capacitors C'_g and C'_w . We show in a subsequent section that C_w , as determined by independent measurements of ΔQ and ΔV_w , is a function of the strength of the discharge and so of both V_a and the initial state of the cell. This nonlinearity is attributable to lateral spreading of the discharge and consequently of the surface charge distribution and its dependence upon the strength of the discharge. It is not correct, then, to infer the voltage transfer ΔV_w from measurements of the charge transfer ΔQ . The derivation of the quantities V_w and V_g is not strictly correct in view of the nonlinearity of the capacitance but is justified as a reasonable approximation because of the relative magnitudes of C'_w and C'_g . If one uses the simplified equivalent circuit of Fig. 2(b), changes in V_a appear as changes in V_g , and this is approximately correct regardless of nonlinearities as long as C'_g is much smaller than C'_w .

During the discharge the potential distribution in the gas space is drastically different from that in the absence of the discharge. This is accounted for by the dependent generator i_g , since the space charging currents are seen at the terminals as part of the gas discharge current waveform.

Figure 3 shows the time dependence of the gas voltage V_g following an abrupt positive excursion of the applied voltage V_a . A positive initial value of V_w is assumed. After a delay, a discharge forms provided the peak gas voltage $V_{go} = V_a + V_w$ is sufficiently large. Voltage V_{go} is called the initial gas voltage. The discharge current deposits charge upon C_w , reducing V_w and hence V_g . The reduction in V_g quenches the discharge, although a "tail" of charge flow persists for several microseconds. The final value of V_g is the residual gas voltage V_{gr} . The change in V_w , $\Delta V_w = V_{gr} - V_{go}$, has in this case a magnitude larger

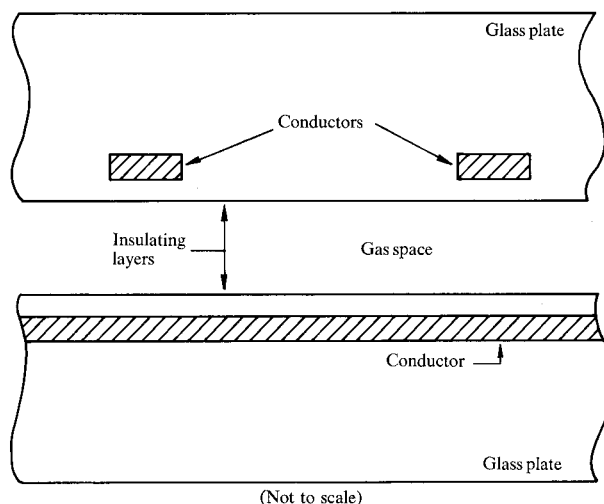


Figure 1 Simplified cross section of an ac gas display panel.

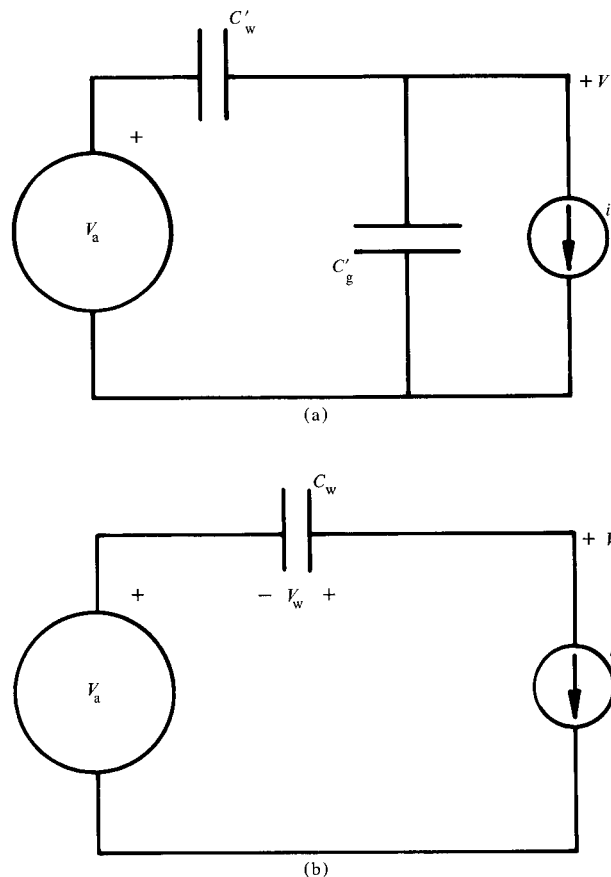


Figure 2 Cell equivalent circuits: (a) complete cell equivalent circuit; (b) approximate cell equivalent circuit.

than V_w , so the final value of V_w is negative. In normal panel operation the next excursion of V_a is negative, so that V_a and V_w are again additive and produce a discharge of the opposite sense. Thus, an alternating V_a produces in

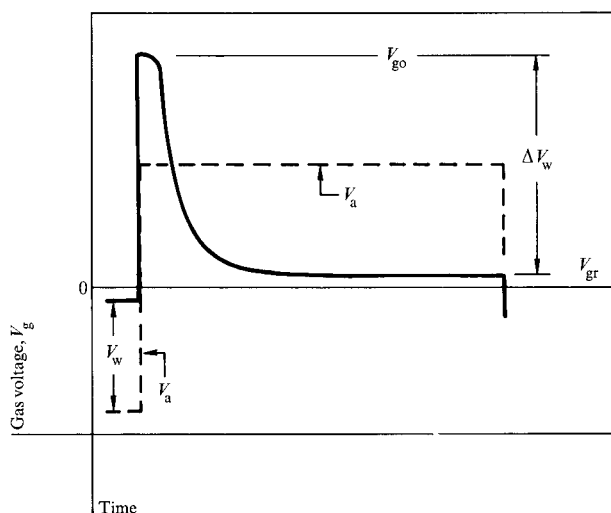


Figure 3 Gas voltage waveform following a step in applied voltage.

the steady state an alternating series of discharges which, under appropriate conditions, is stable [4-6]. The dependence of $|\Delta V_w|$ upon V_{go} is called the voltage transfer characteristic. We have found it to be remarkably independent of the initial state of the cell at the time of its measurement and of the particular sequence of pulses used in the measurement, while there are considerable differences in measured charge transfer under those different conditions.

Measurement of voltage transfer characteristic

We now describe a new method of measuring the voltage transfer characteristic of a cell. The only previous direct method known to the authors is that of Petty [7]. Weber described an indirect measurement of the stable operating regions of a voltage transfer curve [8]. He infers the voltage transfer from the measured charge transfer and the estimated cell capacitance. He acknowledges that the capacitance is not known precisely and that its dependence upon the intensity of the discharge is not taken into account. The motivation for some of the differences between the new method and Petty's is described in the discussion which follows.

The strategy for the new measurement is to establish a steady state operating condition, determine its coordinates on the transfer curve by finding the applied voltage amplitude needed to produce particular changes in that state, and then measure the remainder of the curve relative to the steady state operating point. The latter involves producing known perturbations in V_{go} by means of the applied voltage and then testing for the resultant changes in ΔV_w by finding the subsequent applied voltage

changes which exactly restore the original operating point. Less voltage is needed to restore the perturbation than to produce a "standard" discharge of reasonable amplitude following the perturbation, particularly when the perturbation is large, as it is when measuring the lower part of the transfer curve. This is particularly important when the test cell is part of a matrix, since the higher voltages cause spurious discharges in nearby cells which cloud the measurements.

The available indicators of responses of the operating point of the cells are discharge current and light intensity, and derived quantities such as their integrals. Since these quantities depend to some extent on the initial state of the cell as well as on the strength of the discharge, the choice of indicator must be confirmed empirically. The indicator used here is the peak discharge current amplitude due to the first sustain pulse following the restoring pulse. This current peak is set equal to the amplitude of subsequent sustain discharges by adjusting the restoring pulse amplitude, at which condition the restoring pulse is taken to have exactly corrected the perturbation. Using the discharge amplitude due to the following sustain pulse rather than that due to the restoring pulse itself has these advantages: First, the wall voltage after a restoring pulse of proper amplitude is exactly the same as in the steady sustain condition, so that the peak discharge currents are being compared for firings with the same initial voltage conditions. Second, the amplitude of the peak current or light due to the sustain discharge is much greater than that due to the restoring discharge when the perturbation is large and is more sensitive to the amplitude of the restoring pulse.

The discharge component of current is resolved from the total current waveform, which includes the much larger displacement current by means of special measuring apparatus described elsewhere [2]. In brief, the displacement current and the capacitively coupled interference from the applied voltage are eliminated by differential measuring techniques. The charge transfer is measured by means of electronic integration of the discharge current at the output of a boxcar averager.

The new voltage transfer measurement involves two steps: the determination of the voltage transfer coordinates ΔV_{ws} and V_{gs} of the cell sustained in the "on" stable state, and the determination of the voltage transfer curve relative to that sustain point. The first step, measurement of the coordinates of the sustain point, is illustrated in Fig. 4. It makes use of the special "perfect" erase and "perfect" write pulse amplitudes $V_a = V_{op}$ and V_{1p} , respectively, which result in transfer of a voltage equal in magnitude to the wall voltage V_{ws} of the steady "on" condition:

$$\Delta V_w = -V_{ws} = \Delta V_{ws}/2.$$

These pulses result in erasure to exactly zero wall voltage or writing to exactly V_{ws} in one pulse period. The cell is initially sustaining "on" with an applied symmetrical square wave of amplitude $V_a = V_s$. An erase pulse of amplitude V_{op} is substituted for a sustain pulse. The proper erase amplitude is indicated by the absence of discharge activity over some reasonably large number of subsequent sustain cycles. As an aid to unambiguous identification of the perfect erase pulse amplitude, it is useful to use a sustain amplitude as close as practical to the maximum for which erasure is possible. The erase amplitude range is very narrow for this condition, minimizing the ambiguity in V_{op} . A perfect write pulse is then applied, which is identified by the equality of the amplitude of the discharge current due to the first subsequent sustain firing to those of following sustain firings. Knowing V_{op} , V_{1p} , and V_s , one may find the coordinates of the "on" sustain point on the voltage transfer curve, ΔV_{ws} and V_{gs} , as follows.

The perfect erase pulse and the perfect write pulse each transfer the same amount of voltage, since the former reduces the wall voltage from V_{ws} to zero and the latter from zero to $-V_{ws}$. Consequently, the initial gas voltages must be the same in the two cases provided the same voltage transfer curve applies. The correctness of this assumption is tested by the self consistency of the measured curve. For perfect erasure the initial gas voltage is

$$V_{go} = V_{op} + V_{ws},$$

while for perfect write, it is simply

$$V_{go} = V_{1p}.$$

Consequently,

$$V_{op} + V_{ws} = V_{1p};$$

$$V_{ws} = V_{1p} - V_{op}.$$

From the condition for stable operation,

$$|\Delta V_{ws}| = 2V_{ws} = 2(V_{1p} - V_{op}); \quad (3)$$

$$V_{gs} = V_s + V_{ws} = V_s + V_{1p} - V_{op}. \quad (4)$$

Equations (3) and (4) define the coordinates of the sustain point.

The second step, plotting the curve relative to the measured sustain point, is illustrated in Fig. 5. It uses a one-cycle sequence of test pulses applied at intervals with the cell sustaining "on" at the beginning of the test. A point on the curve is determined by applying an erase pulse during the first half cycle, followed immediately by a write pulse in the second half cycle. The test value of V_g is determined by the amplitude of the erase pulse, and the corresponding value of ΔV_w is determined by the amplitude of the write pulse needed to restore precisely the voltage transferred by the erase, as indicated by equality

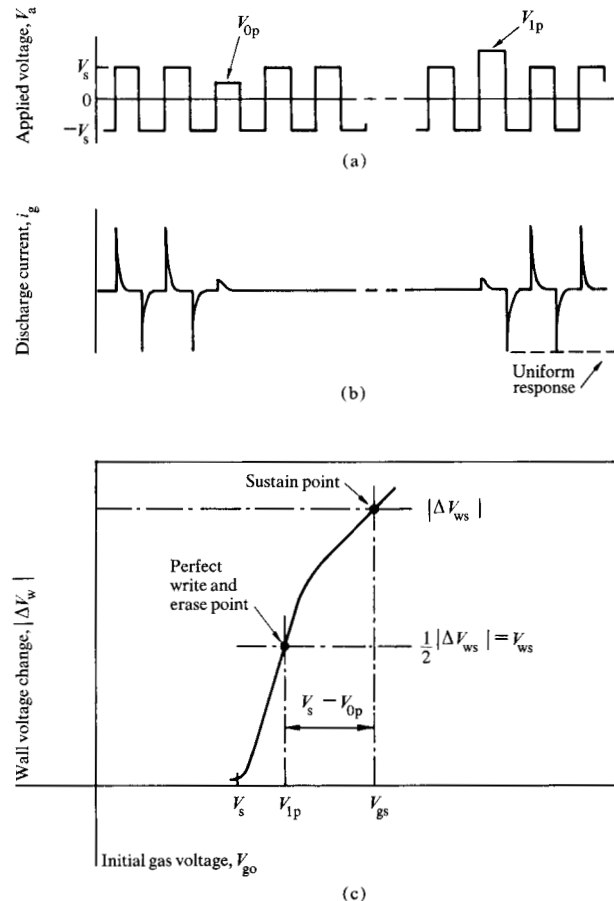


Figure 4 Determining the sustain point on the voltage transfer curve. (a) Applied voltage waveform; (b) discharge current waveform; and (c) determining the sustain point using perfect erase and write amplitudes.

of the first and subsequent sustain firing after the write. From the erase pulse amplitude V_{op} ,

$$V_{go} = V_0 + V_{ws} = V_0 + V_{gs} - V_s = V_{gs} - (V_s - V_0). \quad (5)$$

Since the write and erase pulses transfer the same magnitude of voltage, the magnitude of the initial gas voltages in the two cases is the same, while the sign is opposite. If the write pulse amplitude is V_1 ,

$$V_0 + V_{ws} = -(V_1 + \Delta V_w + V_{ws}).$$

This sign accounts for the polarity inversion between successive half cycles. Voltage V_0 is positive and ΔV_w is taken with the sign appropriate to the erase operation. Voltage V_1 is negative while V_{ws} is positive. Solving for ΔV_w ,

$$\Delta V_w = -(V_1 + V_0 + 2V_{ws}) = -(V_1 + V_0 + |\Delta V_{ws}|),$$

$$|\Delta V_w| = |\Delta V_{ws}| - (|V_1| - V_0). \quad (6)$$

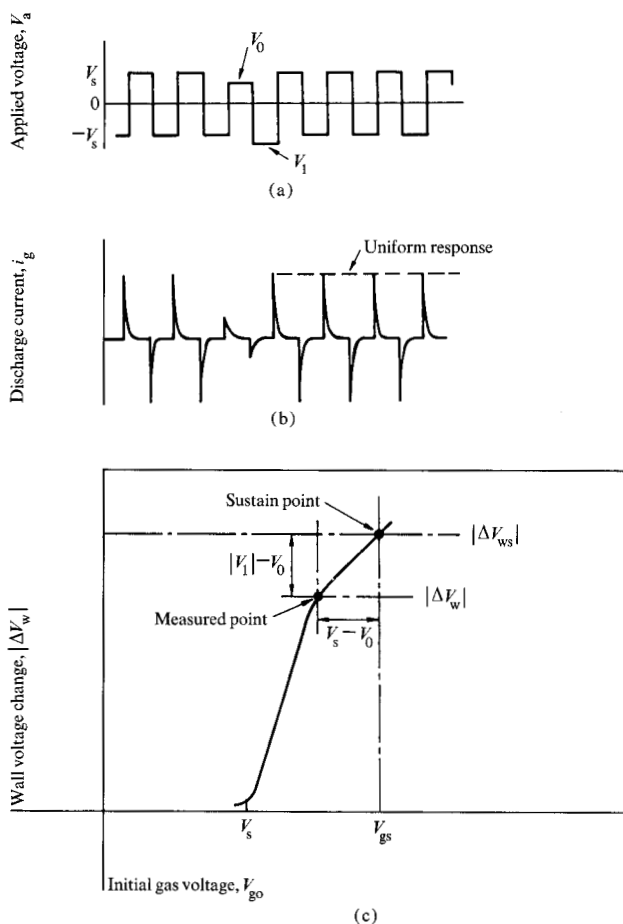


Figure 5 Finding a point on the voltage transfer curve. (a) Applied voltage waveform; (b) discharge current waveform; and (c) determining the coordinates of the point from the erase and write amplitudes.

Equations (5) and (6) define the voltage transfer curve relative to the coordinates of the sustain point.

A voltage transfer curve determined by this method appears in Fig. 6. The minimum and maximum sustain amplitudes for stable operation are defined by the V_g intercepts of the two lines of slope two tangent to the measured curve.

These agree with directly measured values to within one percent in this case, and generally agree to better than two percent. The minimum sustain is determined by spontaneous extinction of the cell while the maximum is determined by failure of the erase operation. The voltage transfer due to an erase pulse equal to the measured perfect erase, determined from this measured curve, is equal to within one percent to one-half the sustain voltage transfer ΔV_{ws} , as determined from step one of the measurement. This establishes the consistency of the shape of the curve measured in step two with the determination of the sustain coordinates in step one. This is notable because the perfect write pulse of step one was determined

at a time when the entire panel had been extinguished for 100 sustain cycles, while for all of the other steps the panel was sustaining in the "on" state.

Properties of voltage and charge transfer

The following are some of the more significant observations about the detailed operation of ac gas display cells determined from measurements of the type described above, and from other measurements by methods derived from those described but differing in the initial state of the cell. These observations apply to cells which have been active or in proximity to active cells some reasonable percentage of the time in the few minutes before the tests. Regions which have become "cold" through inactivity are commonly observed to require prolonged overvoltage to reinitiate discharges. Since the time required for discharges to go to completion is found to depend strongly upon initial conditions and peak gas voltage, the conclusions reached here are based on pulse widths sufficient to permit complete charge transfer. The characteristics of voltage and charge transfer for shorter duration pulses for which the discharges are incomplete, while of considerable practical interest, are not discussed here. The techniques used here are applicable to their study.

1. The voltage transfer characteristic, above the lower knee of the curve, is very nearly independent of the initial state of the cell and the degree of priming from discharges in adjacent cells. However, in the absence of such priming, the "off" state discharges represented by the region of the curve below the lower knee gradually go to zero, substantially vanishing after about ten sustain cycles following a perfect erase operation.
2. The charge transfer in response to a given peak gas voltage, in contrast to voltage transfer, does depend on the initial condition of the cell. This is equivalent to a dependence of the effective wall capacitance on initial conditions. If the charge and voltage transfer are measured together, curves of voltage and charge transfer as functions of peak gas voltage are found to have different shapes. The equivalent wall capacitance can be determined for the particular condition of the measurement as a function of peak gas voltage by taking the ratio of the charge and voltage transfer at each point. This quantity is shown in Fig. 7 superimposed on the voltage transfer curve. The cell was initially sustaining at the maximum sustain amplitude with no other cells lighted. The charge transfer was measured for the discharge due to the perturbing erase pulse of the voltage transfer measurement. The dependence of the effective wall capacitance upon the strength of the discharge is apparent and is attributable to variation in the lateral spread of the discharges.

Another special case of particular interest in practical applications [9-11] is the comparison of voltage and charge transfer for discharges at the same peak initial gas voltage, $V_g = V_{gs}$, but with different initial wall voltages, $V_w = V_{ws}$ and $V_w = 0$. Measurements reveal that equal voltage transfer occurs in these two cases even though a substantially different charge transfer occurs. In a measurement on a typical panel cell made near the maximum sustain point where the sensitivity of charge transfer to initial conditions is the smallest in the sustain region, 74 percent more charge is transferred when $V_w = 0$ and $V_a = V_{gs}$ than in the steady state sustain condition, $V_w = V_{ws}$ and $V_a = V_s$. A corresponding difference in the lateral spread of the glow is observed, particularly along the panel conductor carrying the high voltage. The measured voltage transfer differs by only 0.2 percent, which is within the experimental error. The dramatic increase in the charge transferred when $V_a = V_{gs}$ may be attributable to the fact that the entire length of one of the conductors is above the firing voltage, thus permitting the glow to spread beyond the immediate vicinity of the conductor crossing. In the steady sustain case, the wall charge which contributes nearly half of the initial gas voltage is more confined to the vicinity of the conductor crossing.

3. The residual gas voltage at the conclusion of the discharges, equal to the difference between the voltage transferred and the peak gas voltage, is relatively small in the steady state condition, typically on the order of three volts, compared to initial gas voltages of 180 volts near the high voltage end of the sustain region. This contrasts with typical extinction voltages of several tens of volts in dc glow discharges and is attributed by Sahni and Lanza [3] to continued charge transfer to the cell walls as the discharge activity decays.

Conclusions

New measuring techniques have been used to obtain accurate and complete information about the dependence of voltage and charge transfer upon the initial gas voltage and upon the history and environment of the test cell. In general, the voltage transfer is found to be virtually independent of history and environment, while the charge transfer does depend upon these factors. The dependence of charge transfer upon peak gas voltage differs from that of voltage transfer, so that the effective wall capacitance depends on the strength of the discharge. The residual gas voltage after discharges in the steady sustain condition is found to be only a few percent of the peak gas voltage.

Acknowledgments

J. J. Hall suggested and encouraged this line of investigation. The authors interacted closely with O. Sahni and C.

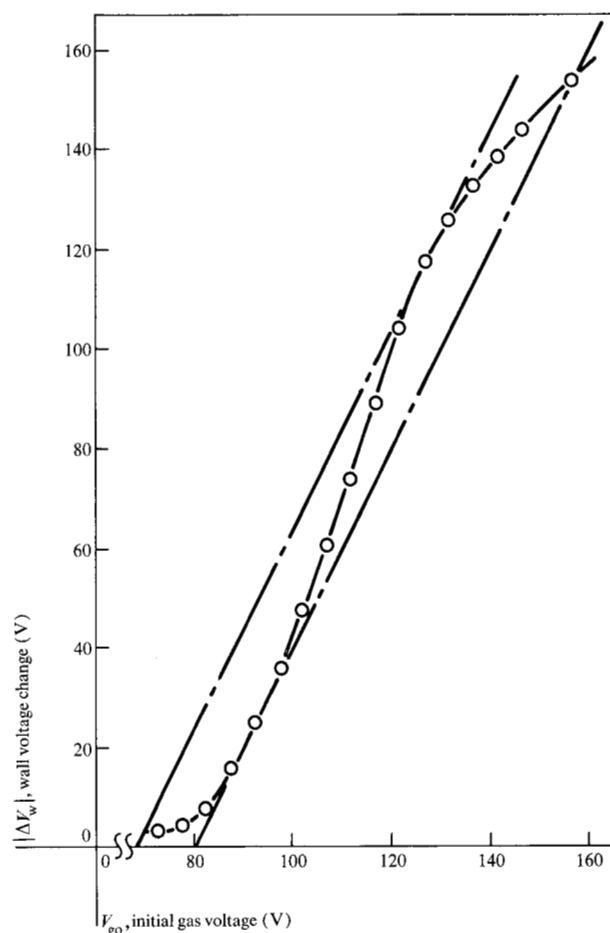
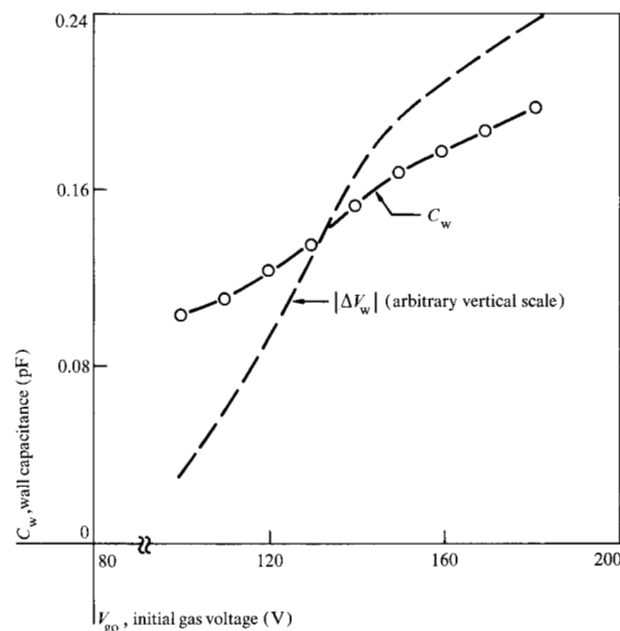


Figure 6 Typical measured voltage transfer curve.

Figure 7 Measured effective wall capacitance as a function of peak gas voltage, superimposed on the voltage transfer curve.



Lanza in the course of this work. The gas panel technology research group under K. C. Park supplied us with many experimental panels. Helpful suggestions were given by T. N. Criscimagna, IBM Kingston. R. Abbatecola and N. M. Payes provided technical assistance.

References

1. C. Lanza, "Analysis of an AC Gas Display Panel," *IBM J. Res. Develop.* **18**, 232 (1974).
2. E. S. Schlig, G. R. Stilwell, Jr., C. Lanza, and O. Sahni, "Characterization and Numerical Modeling of AC Gas Discharge Display Panel Cells," *Research Report RC 6236*, IBM Thomas J. Watson Research Center, Yorktown Heights, NY, 1976.
3. O. Sahni and C. Lanza, "Origin of the Bistable Operating Margin in AC Plasma Display Panel Cells," *Conf. Rec. 1976 Biennial Display Conf.*, New York, Oct. 12-14, 1976, p. 114. Also, O. Sahni and C. Lanza, "Origin of the Bistable Voltage Margin in the AC Plasma Display Panel," *IEEE Trans. Electron Devices* **ED-24**, 853 (1977).
4. R. L. Johnson, D. L. Bitzer, and H. G. Slottow, "The Device Characteristics of the Plasma Display Element," *IEEE Trans. Electron Devices* **ED-18**, 642 (1971).
5. H. G. Slottow and W. D. Petty, "Stability of Discharge Series in the Plasma Display Panel," *IEEE Trans. Electron Devices* **ED-18**, 650 (1971).
6. H. G. Slottow, "The Voltage Transfer Curve and Stability Criteria in the Theory of the A. C. Plasma Display," *Conf. Rec. 1976 Biennial Display Conf.*, New York, Oct. 12-14, 1976, p. 110. Also in *IEEE Trans. Electron Devices* **ED-24**, 848 (1977).
7. W. D. Petty, "Multiple States and Variable Intensity in the Plasma Display Panel," *Coordinated Science Laboratory Report No. R-497*, University of Illinois, Urbana, Nov. 1970, Appendix A.
8. L. F. Weber, "Measurement of Wall Charge and Capacitance Variation for a Single Cell in the AC Plasma Display Panel," *Conf. Rec. 1976 Biennial Display Conf.*, New York, Oct. 12-14, 1976, p. 39. Also in *IEEE Trans. Electron Devices* **ED-24**, 864 (1977).
9. G. R. Stilwell, Jr. and E. S. Schlig, "Nondestructive Graphic Cursors and Light-Pen Tracking on AC Gas-Discharge Display Panels," *Conf. Rec. 1976 Biennial Display Conf.*, New York, Oct. 12-14, 1976, p. 121. Also in *IEEE Trans. Electron Devices* **ED-24**, 873 (1977).
10. R. A. Strom, "High-Speed Low-Cost Selection Circuitry for Large Area Plasma Displays," *Conf. Rec. 1976 Biennial Display Conf.*, New York, Oct. 12-14, 1976, p. 128. Also in *IEEE Trans. Electron Devices* **ED-24**, 878 (1977).
11. G. R. Stilwell, Jr. and E. S. Schlig, "Precise State Control of AC Gas-Discharge Displays," *IEEE Trans. Electron Devices* **ED-24**, 1125 (1977).

Received March 25, 1977; revised September 23, 1977

E. S. Schlig is located at the IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598; G. R. Stilwell, Jr. is located at the IBM System Communications Division laboratory, Research Triangle Park, North Carolina 27709.